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Editorial

From Safety to Sustainability: Shaping the Next Era of Food Science

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Abstract

This editorial examines the shift of the primary focus in food science from the historically dominant paradigms of "Food Safety" and "Food Security" towards "Safe and Sustainable Food Systems" in response to changing global dynamics and crises. The 20th century, shaped by achievements such as the Green Revolution and Hazard Analysis and Critical Control Points (HACCP), focused on producing plentiful and safe food, but has reached its ecological limits due to intensive use of resources and environmental costs. Today, global supply chains, the climate crisis (with food systems being a major contributor to greenhouse gas emissions), resource constraints, and consumer awareness (food waste, animal welfare, ethical demands) are pushing this discipline toward a "sustainability" focus. Food safety and sustainability are now inseparable disciplines; climate change alters food safety risk maps, and food waste is now recognized as a fundamental safety issue. The future of food science aims to develop ethical and sustainable production processes. Areas of solution include Digitalization and Resource Efficiency (Precision Agriculture, Vertical Farming), The Protein Revolution and Alternative Sources (Plant-Based Foods, Cellular Agriculture, Insects), and Circular Economy and Waste Management (Upcycling, Bio-Packaging). Success requires a systemic transformation covering the entire food system (agriculture, processing, distribution, consumption, waste management) and the holistic consideration of planetary health and human nutrition under the "One Health" approach. Sustainability (meeting the needs of the present without compromising the ability of future generations to meet their own needs) has become the primary priority of food science.

Keywords: food science; food safety; sustainability; safe and sustainable food systems

1. The Birth of a New Paradigm

Food is the most fundamental human right and need. From this perspective, access to safe food is also considered a fundamental human right. For this reason, the field of food science and food safety has primarily been shaped around the concept of "safe food" for many years. Historically, human tragedies and economic disasters have occurred due to food-related problems. These problems have arisen as a result of intentional or unintentional individual behaviors and the failure of governments to protect food quality and safety [1]. As a result of such situations, the Codex Alimentarius Commission defined the concept of food safety, and different quality systems Hazard Analysis and Critical Control Points (HACCP), International Organization for Standardization 22000 (ISO 22000) have been used by food producers in food production [2].

However, today, changing global dynamics such as globalized supply chains, climate change, resource constraints, population growth, nutritional transitions, and consumer demands are moving this discipline beyond merely ensuring "Food Safety", bringing the paradigm of safe and sustainable food systems on the agenda. This is because, at the point we have reached today, the responsibility is not only to produce food in high quantities and in a way that will not harm the consumer, but also to produce it sustainably, considering the future of both the consumer and nature.

This editorial aims to outline a framework by addressing the status of the traditional food safety agenda, the areas of overlap between sustainability and safety, and future research and policy perspectives for the next era of food science.

2. Historical Transformation of Food Science: The Safety-Focused Era (20th Century)

The first great era of food science was fundamentally shaped around the concepts of Food Security (producing enough food for everyone) and Food Safety (preventing harm that may originate from food). In this context, there are two important concepts that need to be mentioned: the Green Revolution and HACCP. Ensuring a plentiful and safe food supply for the growing population is considered to be the most important focus of food science in the 20th century.

To feed the rapidly increasing urban population following the Industrial Revolution, the primary goal of food production became volume and efficiency. The Green Revolution (1950s–1970s) began in 1944 when the Rockefeller Foundation established an institute to improve the agricultural production of Mexican farms. As a result of these efforts, Mexico went from having to import half of its wheat to becoming self-sufficient in 1956 and reached a position where it could export half a million tons of wheat in 1964. However, this increase in efficiency came at a cost, including intense chemical use, the widespread adoption of monoculture farming, and the disregard for environmental sustainability [3].

This large-scale production resulting from the Green Revolution opened the door to standardized products with long shelf lives and year-round accessibility, and food science met this demand by perfecting pasteurization, freezing, and preservation technologies. Having increased efficiency for food security, food science subsequently also started to improve food quality and protect public health. The development of safety standards such as HACCP, which arose from this need, ensured the control of fundamental safety concerns as the greatest achievement of this first era. The HACCP food quality system, developed by NASA in the 1960s, further advanced food safety systems over time with the formation of an International HACCP alliance in 1994 [4]. By the 2000s, the concept of food safety gained importance, and the HACCP system became a crucial quality tool for companies [5].

Food production and consumption processes, and consequently global food risks, are increasing every day, and the needs of consumers and the market are constantly changing. Since 1961, the per capita food supply has increased by more than 30%, which has led to increased use of nitrogen fertilizers (an increase of approximately 800%) and water resources for irrigation (an increase of approximately 100%) [6].

3. Crises and the Necessities of a New Paradigm

The assumption that the efficiency model, brought on by the Green Revolution, has reached its ecological limits within today's global food production process is being considered. Soby [7] emphasized approximately 12 years ago that although a viable and acceptable alternative to the current food production paradigm is not presently available, the role of increased food production must be examined in the context of irreparable environmental damage and as a driving force in population growth. It is inevitable that the future green revolution will be linked to sustainability [8]. In short, today's food agenda has shifted from the key point of "safety" to "sustainability". In this context, it becomes important to thoroughly analyze the role of climate, resource use, and consumer preferences.

3.1 Climate and Resource Crisis

Food systems are significant production systems in terms of global greenhouse gas emissions. Crippa *et al.* (2021) [9] created a database for this purpose, providing complete and consistent data on greenhouse gas emissions originating from the global food system, across time and space, including production to consumption, processing, transport, and packaging. According to these data, the largest contribution to greenhouse gas emissions comes from agriculture and land use/land use change activities (71%), while the remainder originates from supply chain activities (retail, transport, consumption, fuel production, waste management, industrial processes, and packaging) [9]. This data also reported that air pollutant emissions from food production systems have steadily increased over the last fifty years, originating from food systems. In 2018, over half of total nitrogen (N) emissions (and 87% of ammonia) and up to 35% of particulate matter emissions originated from food systems. Food system emissions have been identified as responsible for approximately 22.4% of global deaths attributable to poor air quality and 1.4% of global crop production losses [10]. These numbers are too serious to ignore.

In addition, irregular rainfall, droughts, and extreme weather events threaten traditional agricultural regions. Both climate variability and climate change are considered to threaten the safety of the food supply chain in different ways. These threats include a scarcity of safe water for irrigating agricultural products, increased pesticide use due to pest resistance, the difficulty of achieving a well-controlled cold chain and subsequent temperature violation, and sudden floods causing chemical pollutants to run off into natural waterways [11]. As a result of all these processes, as the cost and risk of agricultural production have increased, the livestock sector, in particular, has started to be questioned due to its creation of a large land and water footprint [12].

3.2 Consumer Awareness and Ethical Demands

Today, consumers are no longer just asking what the food provides them; they are also asking where it comes from, how it is produced, and how it affects the planet. Within this context, animal welfare, fair trade, and local production become important issues, and the loss or waste of global food (from production to consumption) clearly demonstrates the inefficiency of the current system. Food waste is considered one of the most significant economic and environmental problems of the 21st Century [13].

In this complex picture, meat consumption, an important component of nutrition, is considered one of the main driving forces of global environmental change due to its multi-faceted dimensions, such as greenhouse gas emissions, land and water use, animal welfare concerns, impacts on human health, and modern agricultural practices [12]. Comparative studies on consumer acceptance emphasize the importance for alternative protein producers to explore new markets and approach these markets with the right strategies, especially in developing countries where meat consumption continues to increase [14]. Therefore, the PBM (plant-based meat) market is predicted to grow in the coming period due to its increasing awareness, familiarity, and knowledge. It is considered critically important for companies aiming for success in this market to focus on potential beneficial areas such as health, environment, and ethics, which will help consumers adopt PBM alternatives to influence their target audiences [15].

4. Areas of Solution and Innovation of the New Era

The next era in food science lies in developing ethical and sustainable production processes at the intersection of traditional agriculture and high-tech food science, focusing on the goal of feeding billions of people within the planet's boundaries. In this context, possible future scenarios can be predicted to include:

4.1 Digitalization and Resource Efficiency

Precision Agriculture: Utilizing Artificial Intelligence (AI), the Internet of Things (IoT), and satellite imagery to determine the minimum amount of water, fertilizer, or pesticide needed for each plant/animal. This will reduce the environmental impact while lowering input costs to more optimally use scarce resources.

Vertical Farming: Conducting agricultural production in closed, controlled environments to provide fresh produce to urban populations and minimize land use, helping to move towards the goal of localizing agricultural production.

Biotechnology: Increasing the climate resilience of raw food materials, enhancing nutritional value, and reducing allergens through genetic engineering.

Process Optimization: Integrating computer and artificial intelligence technologies into food production processes to determine optimal production conditions and prevent the waste of raw materials, labor, and energy.

4.2 The Protein Revolution and Alternative Sources

It is anticipated that protein sources will inevitably diversify in future food systems, and consequently, the dependence on animal husbandry will also decrease:

Cellular Agriculture: Producing meat, seafood, or milk in a laboratory environment by taking cells from animals, thereby significantly reducing the land, water, and greenhouse gas footprint of conventional animal husbandry.

Cultured meat (also known as *in vitro* meat, lab-grown meat, or artificial meat), developed to meet increasing food demand alongside the growing human population, is presented as an alternative solution for individuals who wish to continue consuming meat but do so in a more responsible manner [16]. The recent pandemic and the increase in global demand for meat production have highlighted the necessity for developing alternative systems to traditional animal husbandry [17]. Cultured meat production is being evaluated as an alternative to the problems caused by traditional systems. This system has the potential to be a solution for issues such as animal slaughter, foodborne illnesses, antibiotic resistance, excessive resource use, and greenhouse gas emissions [18]. Cultured meat technology, while contributing to environmental protection and animal welfare, also raises ethical and cultural discussions, such as consumer acceptance, whether it is a "natural" product, and its compliance with halal-kosher traditions [16,19].

Insects (Entomophagy): Making insects an important sustainable protein source in the feed industry and food supplements due to their high protein and micronutrient content, and minimal land and water requirements. Implementing R&D processes for insect-based food products.

As the global population increases and environmental concerns intensify, adopting more sustainable protein sources is becoming increasingly important [20]. The pursuit of alternatives to traditional animal protein sources plays a critical role in the ability of food systems to achieve sustainability goals. A significant alternative to laboratory-produced animal products is edible insects (entomophagy). Insects are thought to become a potential global solution to this problem due to their nutritional profiles and low environmental footprints [21]. Insects possess a source of high-quality protein, polyunsaturated fatty acids, fiber, vitamins, and minerals [22]. In addition, they also contain various bioactive compounds such as antioxidants, antihypertensives, anti-inflammatories, antimicrobials, and immunomodulatory agents, which have a positive effect on human health [23]. Furthermore, insect farming has also been confirmed to have various beneficial environmental effects. The use of edible insects as food and feed is also thought to significantly improve the environmental sustainability of food [24].

Currently, the consumption of insects as food is observed in certain regions of the world. It is reported that billions of people worldwide consume over 1900 species of insects [25]. These include caterpillars, wasps, ants, bees, grasshoppers, crickets, cicadas, aphids, termites, dragonflies, and flies. More than 500 edible insect species have been recorded in Mexico [26]. Insects have a potential not only for humans but also as a source of nutrients and active compounds for poultry [21]. However, the integration of insects into the global food system brings significant challenges that must be overcome, both in terms of consumer acceptance and safety. These risks are:

Allergen Risk: Current information regarding the allergenicity of edible insects is still very limited. They may cross-react with other commonly consumed foods such as crustaceans, as well as common invertebrate respiratory allergens like HDM (House dust mites) [27].

Food Safety and Processing: Risks of microbial contamination (bacteria, fungi), pesticide residues, heavy metals, or accumulation of veterinary drugs are present during the farming and harvesting of insects. This necessitates the development of new industrial standards that must be meticulously controlled, since edible insects are a rich food source that can provide an excellent growth medium for various microorganisms [23]. In addition, the risk of heavy metal accumulation in insects is also of importance [22,28].

Consumer Acceptance (Neophobia): The fundamental motivations determining insect consumption are known to be related to gender, age, sustainability, nutritional value, sensory characteristics, tradition/culture, fear of food novelty, disgust, and familiarity with past experiences. In regions where insects are consumed, these preferences are influenced by factors such as sensory characteristics, availability, and affordability. However, in Western societies, factors such as nutritional value, sustainability, benefits, familiarity and past experience, tradition and culture, fear of food novelty, and disgust are more influential [29]. Changing this perception will require long-term education and marketing strategies since insect consumption is generally negatively reviewed [25].

Production Scalability: Producing high-quality, consistent, and sustainable insect protein on a global scale and in an economically competitive manner involves technological and infrastructural challenges that have not yet been fully resolved. For example, the processing of insects can affect their nutritional value in many ways, the most common is the destruction of vitamins and the denaturation of proteins due to heat [22]. Therefore, a greater number of R&D studies will be needed to ensure the safe production of insect-based food products.

In light of these challenges, it is clear that ensuring future food security and sustainability requires a focus on a diversified protein portfolio, rather than relying on a single alternative protein source. In this portfolio, plant-based nutritional strategies and advanced processed plant proteins should assume a central role as complements to insect-based proteins.

Plant-Based Foods: Producing next-generation substitutes such as fermented fungus (mycoprotein) and algae-based products, in addition to staple sources like soy and peas, in order to reduce the resource consumption caused by livestock farming and promote fair and sustainable production processes.

Plant-based nutrition (especially proteins derived directly from plant sources such as legumes, grains, and nuts) has a lower profile regarding most of the allergen and neophobia risks associated with insect consumption. A study found that plant-based foods are more easily accepted than insects in terms of neophobia [20].

Plant-based diets generally contain higher fiber content and lower saturated fat levels [30]. It is thought that a well-planned diet consisting of whole, plant-based foods, including various vegetables, whole grains, nuts, and legumes, would be a tool that could help physicians and patients in coping with chronic lifestyle diseases that many people struggle with today [31]. Plant-based diets are environmentally more sustainable than meat-based diets and have a lower environmental impact, including lower levels of greenhouse gas emissions [32].

In the future, the importance of plant proteins will further increase thanks to innovation. Advanced processing technologies, such as precision fermentation, algal protein production, and the continuous development of plant-based meat alternatives, are bringing the nutritional value, functionality, and sensory characteristics of plant proteins closer to those of traditional animal products. These developments will make plant-based proteins one of the fundamental pillars shaping the new era of food sciences, both in terms of food safety and sustainability.

4.3 Circular Economy and Waste Management

Developing systems that recycle and adapt food waste to the process, rather than viewing it as a loss, is important for circular sustainability. For this purpose, bio-packaging and upcycling systems, likely to be part of future food processing systems, will become more common.

Bio-Packaging: The proliferation of biodegradable packaging, derived from food waste or algae, to be used instead of petroleum-based plastics.

Upcycling: Converting by-products leftover from food production (e.g., fruit peels, pulp) into new food products with high nutritional value or into bio-packaging.

Supply Chain Optimization: Instant monitoring of supply chains using blockchain technology and AI to identify points where loss and waste occur most frequently, enabling rapid intervention.

5. Integration and Recommendations for Future Directions

5.1 The Intersection of Safety and Sustainability

Food safety is no longer an isolated discipline; it has become associated with broader sustainability goals such as environmental impact, resource efficiency, and social justice. Increasing temperatures and irregular weather conditions caused by global climate change directly affect the toxicological risk maps in food production, complicating food safety.

The fact that a significant portion of the food produced each year is lost or wasted is not only an ethical and environmental disaster but also a fundamental food safety issue since it results from spoilage and contamination.

In this context, it will be of great importance for all food stakeholders involved in food production, from farm to fork, and all scientific disciplines influencing the process to work together to create safer food systems.

5.2 Systemic Approach and One Health

The success of food science in the future is possible through a systemic perspective. A "food system transformation" approach must be adopted, addressing the food system not just as production, but with all its links such as agriculture, processing, distribution, consumption, and waste management.

Furthermore, repositioning food science under the umbrella of One Health is vital. It is estimated that more than 70% of risks to food safety originate from animals. This necessitates food scientists collaborating with veterinarians and environmental scientists to develop integrated solutions, especially concerning antimicrobial resistance and the spread of zoonotic pathogens.

5.3 Research and Policy Directions

The main directions that should be focused on in the coming period are:

Governance-Policy Integration: Effective governance models, multi-stakeholder approaches, and appropriate regulatory frameworks must be developed for safe and sustainable food systems. State policies, laws, control mechanisms, and the media are of great importance.

Metrics and Monitoring: The development of sustainability metrics is necessary; a common methodology has not yet been established in this area. The transparent sharing of integrated sustainability data by all food stakeholders will enable us to better understand the process from production to consumption.

Industry-Academia Collaboration: The transfer of findings produced in academia to the industry and policy spheres will increase the practical relevance of the links between food safety practices and sustainability goals.

6. Conclusion: The New Mission and Call to Action for the Food Scientist

The next era of food science will redefine not only **"what we eat"** but also "**how we produce, how we process, and how we consume**". While safety (sufficient and non-toxic food) remains a fundamental necessity, Sustainability (meeting the needs of the present without compromising the ability of future generations to meet their own needs) is now the primary priority.

This new era demands an interdisciplinary approach from food scientists, requiring not only knowledge of chemistry and microbiology but also data science, environmental engineering, ethics, and circular systems. The future of food will be secured when we succeed in treating planetary health and human nutrition as an entire indivisible concept.

Building a food system that is safe and compatible with the environment for future generations is a result of today's research, policy, and practice preferences. I invite all stakeholders—researchers, industry, regulators, and consumers—to be a part of this transformation.

Perhaps the most critical question of the next era is:

"Will our food merely nourish us, or will it also heal the planet?"

Availability of Data and Materials

There is no data file related to the manuscript.

Author Contributions

SÖ designed the entire manuscript and carried out the manuscript and editorial revisions and served as the corresponding author. The author contributed to critical revision of the manuscript for important intellectual content. The author read and approved the final manuscript. The author has participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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